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Intelligent control of grain drying process using fuzzy logic controller

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Abstract

Controlling grain drying process is always a challenging task for engineers and researchers in food and agricultural sectors since many years ago. The main obstacles to obtain the best control system for the grain drying system are due to the long delay process, highly non-linear behaviour and parameter uncertainties exist in the plant. Applying an intelligent controller such as fuzzy logic controller to a grain drying system is a good choice as fuzzy logic controller is a very powerful control methodology that can estimate functions based on partial knowledge of the system in case of parameter uncertainties and can deal with non-linear behaviour. This paper focused on the design and application of fuzzy logic controller in order to obtain the grain output moisture content close to the set-point in spite of disturbances. Two inputs and one output fuzzy logic controller has been designed to drive the grain flow rate which is used as the manipulated variable. A new algorithm of fuzzy logic controller for a grain drying process has been introduced. Simulation tests have been carried out using the process model developed by Liu and Bakker-Arkema for a cross-flow grain dryer. The overall results from the tests are very promising and the fuzzy logic controller is stable and robust towards input disturbance. Although the design process of fuzzy logic controller is simple; however it provides very fast response to make the grain output moisture content close to the set-point and to reject disturbance exists during the grain drying process.

Key words: Grain drying, fuzzy logic controller, intelligent control, non-linear, uncertainty, agriculture.

Introduction

Grain drying is one of the important processes in food and agriculture sector. This is because grains normally contain high moisture just after being harvested. Drying process needs to take place immediately in order to maintain the quality, freshness and longer life storage. For example, in case of paddy, the moisture content just after harvested is high, ranging 25-40% dry-basis (d.b). The storage of paddy and other type of grains with such high moisture content before milling will cause the development of high temperature, serious deterioration in the form of discoloration and off-odours, and ultimately reduced milling yield due to the growth of moulds and other microorganisms. In another example, fufu flour which is a traditional food from Nigeria, drying process is highly important to increase shelf-life and marketability product. Various drying methods have been implemented, for example by using flash and rotary dryer [12].

Grains took some time to be dried properly. The process to dry germinated seeds used to prepare weaning food for young children took 10 h in a cabinet dryer at 55°C [4]. Germinated grains are reported as an improved diet for children; they have reduced viscosity and increased digestibility. This long delay drying process could be improved if a proper drying control system is implemented.

There are parameter uncertainties or variations in the grain drying process that makes the conventional control of grain drying difficult. A few control strategies have been applied to grain dryer with similar control objectives; stability of the system, accuracy of the product close to desired moisture content and robustness of the controller towards any disturbances. A good literature review about some control strategies in grain dryer can be found from Lutfy *et al.* [7]. The authors reviewed the different control strategies, modelling and simulation techniques, analysis of performance of existing grain drying systems in terms of energy consumption, grain quality all the issues that aid in optimising their operating efficiencies. Solar type grain dryer is also reviewed.

Here are some examples of grain drying control systems developed by researchers. Moreira and Bakker-Arkema [9] developed an adaptive controller based on a continuously updated linear control, for continuous-flow grain dryer control. Their findings have shown that with pole placement controller, the average outlet moisture content to within ±0.1% of the set-point even for significant variation in the inlet moisture content (±2.3%). Other than continuous flow drain dryer, cross-flow dryer is also available. Using similar approach, Nybrant [11] achieved the control objectives. The said controller can tune itself in order to maintain good control despite of disturbance. The author also developed and tested an adaptive controller on laboratory concurrent-flow dryer. By using either final grain temperature or the approximate maximum grain as the controlled variable, a very accurate control of temperatures was obtained.

Fuzzy Logic Controller (FLC) has been reported to be applied in the industries as early as in 1970s. FLC is an intelligent control which attempts to model humans' sense of word, decision making and common sense [10]. It has a capability to link human reasoning and concept formation through fuzzy rules. It also provides a compact structure of rule representation and can estimate functions and control system with partial knowledge of the systems. Therefore, designing a controller using fuzzy rules is very simple yet workable. FLC was successfully implemented in telecommunications, process control, chemical engineering, electrical and computer engineering, robotics, networking, environment and many more [1, 3, 8, 13, 14]. However, not many works were reported in the agricultural sector. An outstanding research has been done by Zhang and Litchfield [15] using FLC to control a grain dryer. The controller was used to obtain outlet maize moisture content between 15 and 16% and at the same time minimizing the outlet maize breakage. Atthajariyakul and Leephakpreeda [2] proposed an adaptive fuzzy logic control to control the system conditions close to the reference value. Case studies of fluidized bed paddy dryer were undertaken and the authors found that the proposed method can be efficiently implemented in the real-time determination and control the optimal conditions. The system maintains the paddy moisture content close to the desired level with efficient energy consumptions.

Realizing all these importance and problems, FLC is proposed to control the grain dryer process in order to achieve desired moisture content. At the same time, the process model developed by Liu and Bakker-Arkema [6] for a cross-flow grain dryer has been used in the simulation work. The main focus of the research is to obtain output moisture content of grain (maize) around 15% regardless the presence of disturbance (i.e. changes in initial grain moisture content). As the author concerned, applying FLC to control cross-flow type grain dryer for the said objective is practically new.

Process model: In the cross-flow grain dryers, the drying air transverses the grain column perpendicular to the downward flow of the grain [6]. The grain column can be viewed as stack of rectangular elements shown Fig. 1. It was assumed that the dryer is operated under standard Midwestern US environmental conditions.

The mathematical model developed for this cross-flow drying was [6]:

$$M_{j+1} = \overline{Mj} - \frac{k_1(\overline{M_j} - M_{e1})\Delta Y}{G_g({}^1/p_g + k_1 c_1 q \overline{M_j} - k_2 c_2 q M_{e1})} \qquad (1)$$

$$a = -20.4 + 0.075T_1 \qquad (2)$$

$$b = 12522 - 37.3T_1 \qquad (3)$$

$$c_1 = \frac{1 - exp\,({}^r/(1.8(T_1+273))^{-r}/618}{1.8(T_1 + 273) - 618} \qquad (4)$$

$$c_2 = \frac{1 - exp\,(({}^{r-b}/(1.8(T_1+273))^{-(r-b)}/618}{1.8(T_1 + 273) - 618} \qquad (5)$$

$$q = \frac{h(0.9H)}{c_a G_a} \qquad (6)$$

$$k_1 = \nu\, exp({}^{-r}/(1.8(T_1 + 273))) \qquad (7)$$

$$Me_1 = 0.01\, exp\,(a + {}^b/(1.8\,(T_1 + 273))) \qquad (8)$$

The description on the notation used in equations can be found from Appendix A.

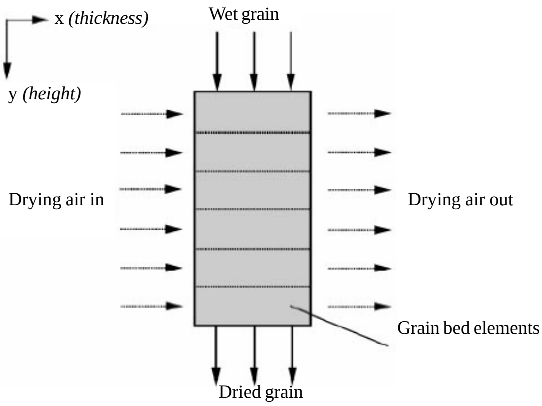

Figure 1. Schematic of cross-flow drying [6].

For the control purpose, the grain flow rate has been chosen as the manipulated variable. The model is reformulated; instead of being fixed, the grain flow rate is now set as the manipulated variable. In the rest of the paper, the reformulated model is used. The output of FLC will be used to drive the grain flow rate to achieve the desired moisture content.

Fuzzy logic controller (FLC) design: The general structure of FLC is shown in Fig. 2. The controller is between pre-processing block and a post-processing block.

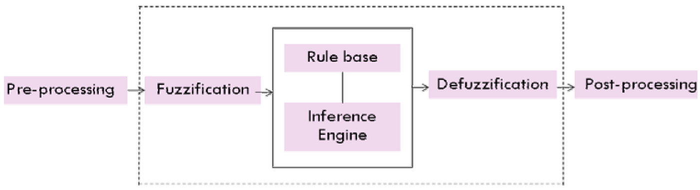

Figure 2. Structure of fuzzy logic controller [5].

Pre-processing block conditions the measurements before they enter to the controller. For a grain dryer case study, pre-processing refers to the data in the universe of discourse of the inputs of the controller; first, error between the desired and the actual grain output moisture content (error) and second, rate of change of error (del_error).

The universe of discourse of an input “error” is from -0.1 to 0.1 and for an input “del_error” is from -0.15 to 0.15. Because of the inputs of the controller are error between the desired and the actual grain output moisture content and rate of change of error or derivative of the error, the designed controller is called proportional derivative (PD) type FLC. After the pre-processing process, the inputs data are being fed into the controller.

Fuzzification is a process within a controller block which converts each piece of input data to degrees of membership by a lookup in one or several membership functions. The fuzzification block thus matches the input data with the conditions of the rules to determine how well the condition of each rule matches the particular input instance. There is a degree of membership for each linguistic term that applies to that input variable. The membership functions of the inputs “error” and “del_error” are shown in Fig. 3.

Rule base is a set of rules defined by the designer to control the controller. Every rule is divided into two parts: condition and conclusion. In this study, the rule knowledge base for the grain flow rate is summarised in Table 1.

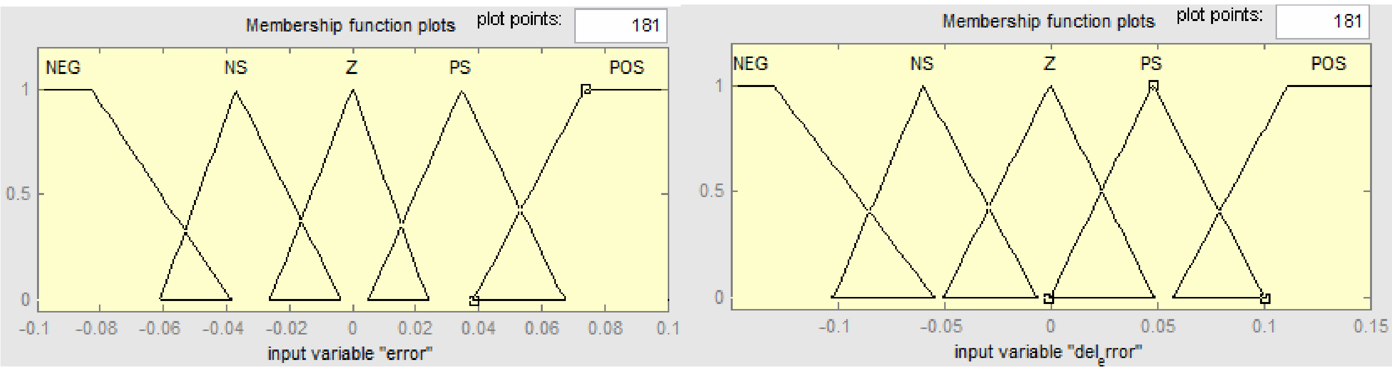

Figure 3. Membership function of two inputs FLC "error" and "del_error".

Table 1. Rule table of FLC for a grain dryer plant.

Δ \ e	NEG	NS	Z	PS	POS
NEG	VS	VS	S	NSS	M
NS	VS	S	NSS	M	NSH
Z	S	NSS	M	NSH	H
PS	NSS	M	NSF	H	H
POS	M	NSF	H	VH	VH

NEG - Negative, N - Not so slow, Z - Zero, PS - Positive small, POS - Positive, VS - Very slow, S - Slow, NSS - Not so slow, M - Medium, NSH - Not so high, H - High, VH - Very High.

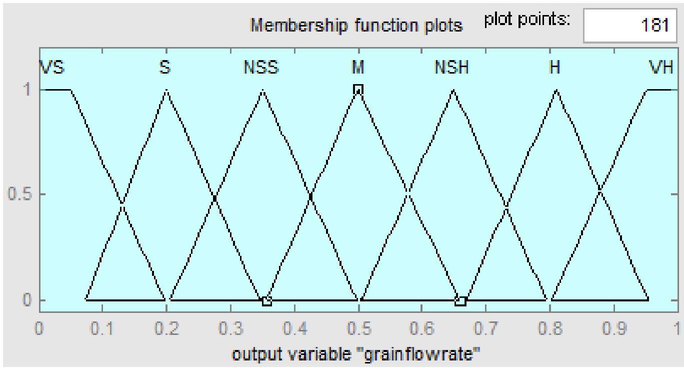

Figure 4. Membership function of FLC output "grainflowrate".

For example, in row 1 column 1, the rule is defined as follows: If *error* is NEG AND *del_error* is NEG, then *grainflowrate* is VS. In general, the structure of rule is as follow:

If *condition(s)* then *consequent*.

Inference engine links the rule given in the knowledge base with the facts provided in the database. There are several inference engines available; one of them is Mamdani Fuzzy Inference System (FIS). The consequent part of Mamdani FIS is membership value. This method is chosen in this study.

Defuzzification is the process of producing a quantifiable result in fuzzy logic. The consequent part of rules is in the form of fuzzy sets and defuzzification would transform this result from a fuzzy set to a crisp number.

Post processing is required when the output is defined on a standard universe must be scaled into engineering units. In this study, the output range is 0 to 1. The scaling is done outside the controller where a proportional gain is added to scale the chosen range of grain flow rate. The output membership function for output of FLC is shown in Fig. 4.

Results and Discussion

The proposed fuzzy control algorithm is tested on the reformulated model, originally developed by Liu and Bakker-Arkema [6]. Based on preliminary test on the grain dryer, the best fit maximum grain flow rate is 23,000 $h^{-1}m^{-2}$.

The first test on the closed-loop system is to track the desired set point of output moisture content of 15%. As expected, the FLC works very well. The controller takes less than 30 seconds to achieve the desired state. The result is given in Fig. 5. Compared to previous works that had been done in similar area, the designed FLC gives superior performance in terms of response time. The system developed by Zhang and Litchfield [15] and Liu and Bakker-Arkema [6] takes hundreds of minutes to reach desired state. The error and rate of change of error signals are given in Fig. 6. The ranges of both errors are relatively small. This is designed through defining small range of membership functions of "error" and "del_error" (refer Fig. 3). After several simulation tests, the optimum range for "error" is from (-0.1 to 1.0) which is ±10% deviation from the desired output and the optimum range for "del_error" is from (-0.15 to 0.15) which is ±15% deviation from the desired output. Small error range produced an output response that is closer to the desired output or in other word, reduced steady state error.

Input step disturbance could occur in the grain drying system. As an example, after the system runs for several times, grains with different initial moisture content are loaded to the dryer. This phenomenon will disturb the normal operation of the drying process and deteriorate the final output moisture content. In the simulation, a step change in initial moisture content describes this phenomenon. Fig. 7 shows a significant step change from 20 to 30% of the initial moisture content at t = 100 s. In this test, after the system is stable and reached the desired output, a step disturbance caused larger error and rate of change of error. The controller adjusts the grain flow rate to run accordingly, referring to the rules specified in the rule table. The FLC is able to reject the input disturbance as shown in Fig. 8.

Conclusions

The objective of this research work was achieved. A FLC has been designed to control a grain dryer that is known with its characteristics; long delay process, non-linear and subject to disturbances and parameter uncertainties. Through simulations, it was found that the FLC could make the grain output moisture content close to the set point in a very short time. At the same time, it is able to reject the presence of input disturbance. Further work can be done to improve the performance of the overall system. Wider operating range and ability to reject different type of disturbances could make the grain dryer system more efficient and robust.

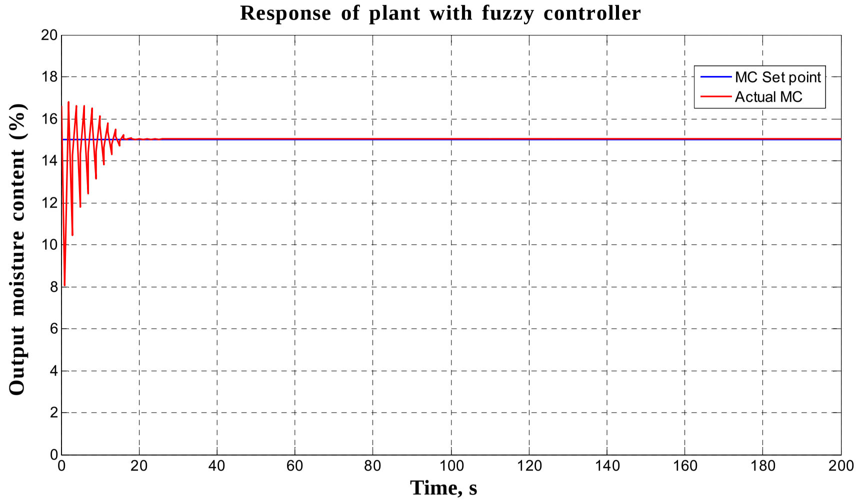

Figure 5. Closed-loop test: Response of plant with FLC. Set-point (output moisture content) = 15%.

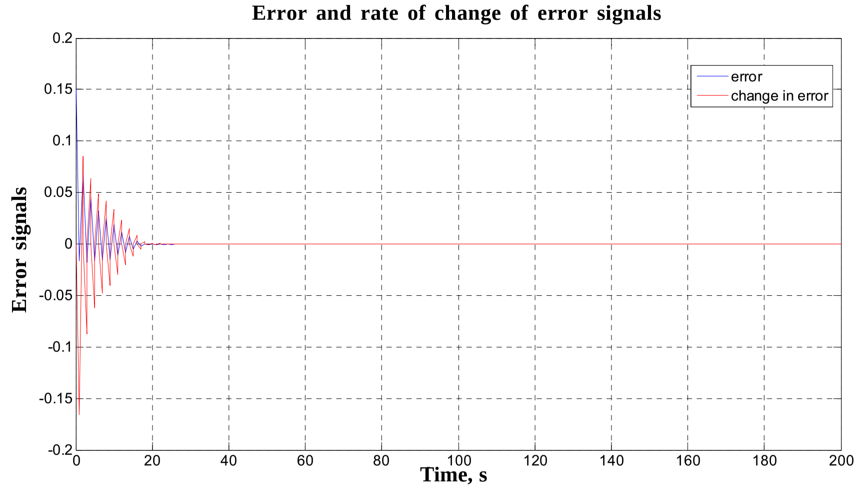

Figure 6. Error and rate of change of error; between actual and desired output moisture content.

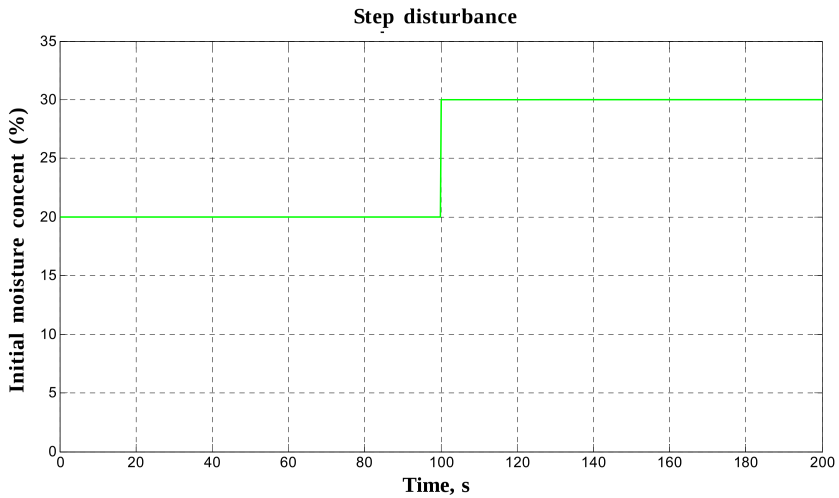

Figure 7. Step change in initial moisture content at t=100s as input disturbance.

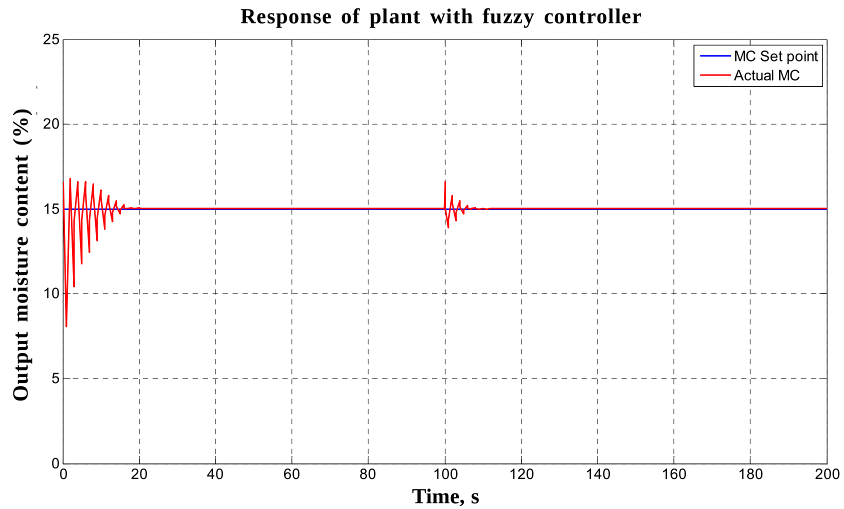

Figure 8. Closed-loop test: Response of plant with input disturbance.

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Appendix A. Notation used in equations:

$A, B, C,$ a, b	coefficients for equilibrium moisture content of maize
c	specific heat, kJ kg^{-1} °C^{-1}
$c_1, c_2,$ c_3, c_4	coefficients for process model
G	flow rate, kg [dry matter] h^{-1} m^{-2}
h	heat of vaporization, kJ kg^{-1}
H	thickness of the grain column, m
H_R	relative humidity, decimal
k	drying constant, h^{-1}
M	grain moisture content, dec., d.b.
$\bar{M}$	average grain moisture content across the grain column, dec., d.b.
n	elements representing a full-size dryer
q	coefficient for the process model
r	exponent for the drying constant, 5032 for maize
T	drying air temperature, °C
v	coefficient for the drying constant, 1941 for maize
x, y	coordinates, m
Y	height of the drying section, m
ΔY	height of a bed element, m
ρ_g	grain density, kg [dry product] m^{-3}
τ	drying time, h
Subscripts	
a	air
e	equilibrium
f	grain outlet
g	grain
i	grain inlet
j	index
t	target value
y	at the position Y above the outlet of the drying section
1	air inlet